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REPORT OF INVESTIGATIONS/1995

Improved Grindability of Taconite Ores by Microwave Heating

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	mm	millimeter
cm^3	cubic centimeter	pct	percent
g	gram	rpm	revolution per minute
kg	kilogram	s	second
kHz	kilohertz	t	metric ton
kW	kilowatt	W/cm^2	watt per square centimeter
kW•h/t	kilowatt hour per metric ton	μm	micrometer
MHz	megahertz	°C	degree Celsius

IMPROVED GRINDABILITY OF TACONITE ORES BY MICROWAVE HEATING

By John W. Walkiewicz,[1] David P. Lindroth,[2] and Andrea E. Clark[3]

ABSTRACT

The U.S. Bureau of Mines has conducted studies to utilize rapid microwave heating to stress fracture ore samples. Iron ores containing hematite, magnetite, and goethite were subjected to microwave energy in batch operations at 3 kW and heated to average maximum temperatures between 840 and 940 °C. Standard Bond grindability tests showed that microwave heating reduced the work index of iron ores by 10 to 24 pct. In a microwave chamber designed to simulate a continuous throughput operation at 3 kW, the grindability of a taconite ore was improved by 13 pct at a bulk temperature of 197 °C. Because stress cracking occurred at a lower temperature, less energy was consumed. To further improve the economics of microwave fracturing, higher powers up to 16 kW were used to rapidly heat samples to relatively low temperatures in a continuous, belt-fed applicator. A significant improvement of grindability was obtained with a larger rod mill feed size in comparison to a minus 6-mesh Bond feed.

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INTRODUCTION

Grinding is the most energy-intensive step in mineral processing. Typically, 50 to 70 pct of the energy used for mineral extraction is consumed during comminution. The energy efficiency of conventional grinding is about 1 pct, with most of the energy wasted as heat generated in the material and equipment. Because of this low efficiency, even the slightest improvement in comminution technology can result in measurable economic savings.

Conventional size reduction is accomplished by compressive force externally applied to the particle. To improve the efficiency of conventional grinding, the current trend is to optimize certain aspects of the comminution cycle, such as employing grinding aids and sophisticated classifier recirculation systems. Little has been done to develop alternatives that utilize tension to break rock, even though the tensile strength may be as little as one-tenth of the compressive strength of the rock. Several schemes have been proposed that do utilize tension forces to break rock. One method uses electrical energy, generally high-voltage, radio-frequency power to cause rapid resistive heating that induces thermal-stress cracking. Another method, employing ultrasonic energy,[4] is used to produce mechanical vibrations within the particles and solid materials at frequencies of 15 to 60 kHz. Preliminary data by Tarpley indicated ultrasonic dry grinding is 4 to 9 times as efficient as conventional grinding, and ultrasonic wet grinding is up to 10 times as efficient as conventional grinding. A two-stage comminution process that employs both electric and ultrasonic energy is described by Parekh and others (*1*).[5] They claim this combination of energy fractures the gangue matrix of the ore and selectively liberates minerals much more efficiently than conventional grinding. None of these novel comminution schemes using tension forces has been commercially developed.

An alternative to electrical resistive heating is microwave heating. Research conducted by the U.S. Bureau of Mines (USBM) (*2-3*) has demonstrated that many minerals of value absorb microwaves and are rapidly heated. The purpose of this report is to show that microwave energy can be used to induce thermal-stress cracking to decrease the energy requirements of grinding selected iron ores. This research is in support of the USBM's program to develop innovative technologies that enhance domestic mineral production.

APPARATUS AND EXPERIMENTAL PROCEDURES

Iron ore samples were obtained from the Cleveland-Cliffs Iron Co. and included a Michigan magnetite (Empire Mine), a martitic hematite (Tilden Mine), and a specular hematite (Republic Mine). Minnesota taconite ores were obtained from the Reserve Mining Co. and Minntac. Each sample was dried and crushed to a minus 6-mesh feed material.

The effects of microwave heating on the iron ores were observed through microscopic examinations of specially prepared specimens. Photomicrographs of microwave-induced cracking were obtained using a JEOL model JSM-T300 scanning electron microscope (SEM). Iron ore specimens no larger than 1 by 3 by 3 cm were cut, ground (240 through 600 grit), and given a final polish with 0.3-μm alumina powder. The sample was coated with a thin layer of colloidal carbon to improve conductivity. Photomicrographs were taken of the sample at magnifications between 35 to 1,500 before and after microwaving. The SEM was used in the backscatter mode to enhance compositional contrast.

The batch-heated iron ores were treated with microwave energy using a 0- to 3-kW, 2,450-MHz industrial power supply (Cober Electronics, Stamford, CT). The applicator was an oven chamber taken from a commercial household unit and modified to accept microwave power via a WR284 waveguide. Sample temperatures were monitored using a type K thermocouple with an ungrounded tip sheathed in Inconel 702 alloys. The thermocouple was inserted through the roof of the oven directly into the sample.

Feed materials for the grind tests were heated in 350-g batches for 210 s. A minimum of 6 kg of minus 6-mesh sample was required for each grindability test.

Taconite samples were also microwaved in a throughput applicator that simulates the continuous flow of a belt-fed applicator. The flowthrough chamber was constructed with a WR975 waveguide and coupled to the 3-kW Cober power supply. A mode-stirring fan and baffles were added to the interior roof of the WR975 waveguide to improve the heating characteristics of the sample by creating a

[4]Tarpley, W. B., Jr., R. C. Arbiter, and G. Moulder. Ultrasound Comminution. Presented at Recent Developments in Comminution Conference, Kona, HI, Dec. 8-13, 1985.

[5]Italic numbers in parentheses refer to items in the list of references at the end of this report.

finely distributed microwave pattern. These modifications improved the uniformity and the rate of sample heating. A sample boat, 2.54 by 10.16 by 30.48 cm was moved through the heating zone inside the applicator by means of a linear gear arrangement and a reversing motor. A taconite sample weighing 1,600 g was microwaved at a power level of 3 kW. A bulk sample temperature was measured with a thermocouple after stirring the sample in a stainless steel pail heated to approximately the same temperature achieved by the microwave sample.

The grindability of the iron ores was determined according to the standard procedure developed by Bond (*4*). The special laboratory-scale grinding device is a Bond ball mill manufactured by Bico-Braun Inc., Burbank, CA. The ball mill was run at 70 rpm with a charge of 285 iron balls ranging in diameter from 19.05 to 38.1 mm and weighing approximately 20,125 g. An initial volume charge of 700 cm^3 of minus 6-mesh iron ore feed was ground in the Bond mill. The minus 100-mesh fraction of the product was discarded and replaced with new feed to keep the mass of the charge constant. This milling cycle was repeated until the net grams of minus 100-mesh material produced per mill revolution (grindability) attained equilibrium with a specified circulating load of 250 pct. The Bond work index (in kilowatt hours per metric ton ore), a constant for any product discard size, is calculated from the following Bond-derived (*5*) equation:

$$W = \frac{1.6\ (P)^{0.5}}{G^{0.82}},$$

where W is the work index, P is the product discard mesh size opening in micrometers, and G is the grindability for the given product mesh size. The work index is defined as the grinding energy required to comminute the material from theoretically infinite feed size to 67 pct minus 200 mesh. It is not the energy needed to grind the ore from a minus 6-mesh feed to the given product discard size.

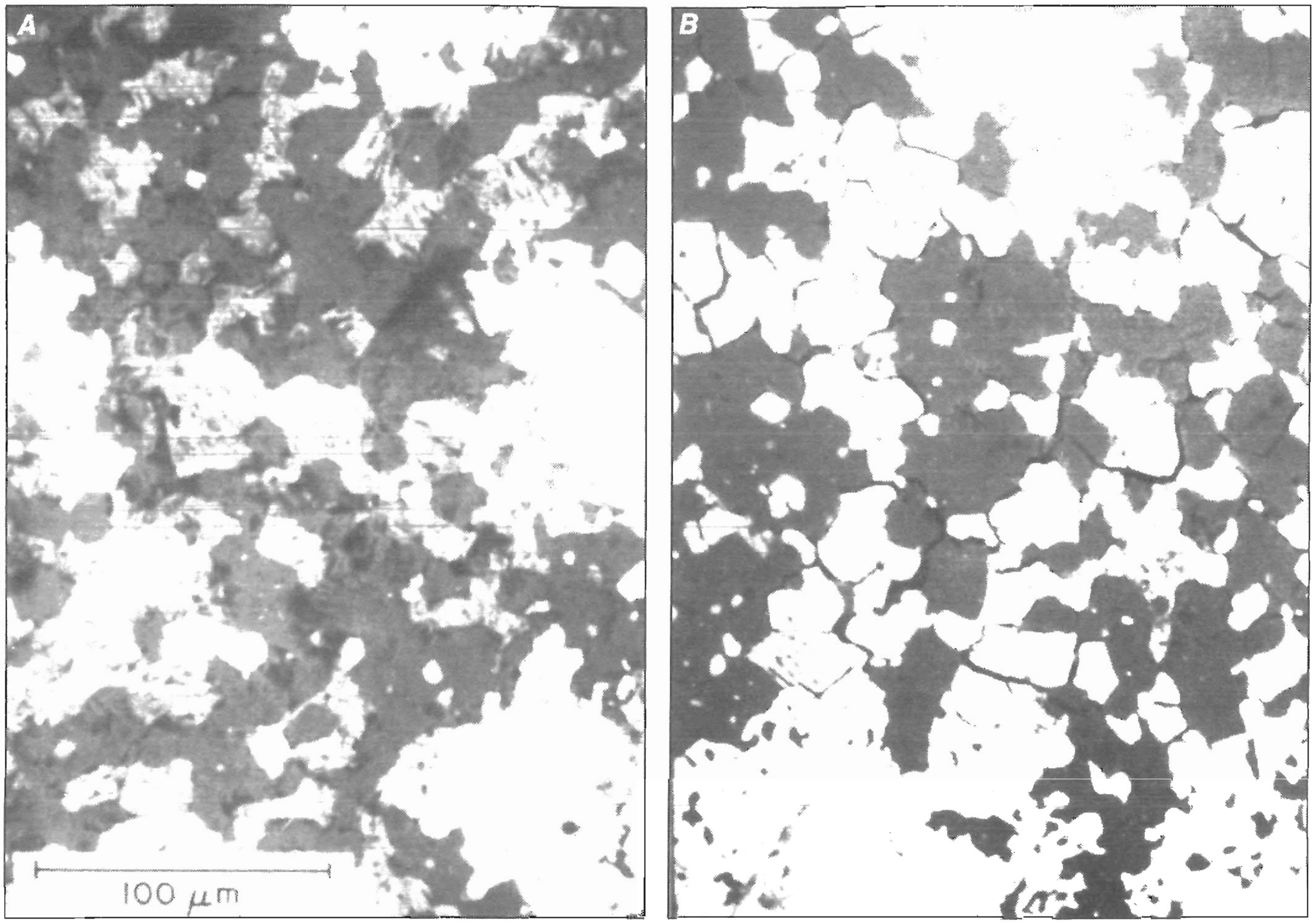
The above equation is Bond's empirical simplification of the theoretically derived equation according to his third theory of comminution. To determine the effect of rapid microwave heating on the grindability, the relative change in the Bond work index before and after microwaving was determined. For this investigation, the simplified equation was found to be a reliable and acceptable means of comparison to assess the effectiveness of microwave-induced cracking to improve the grindability. A more precise value on the work index can be obtained using Bond's revised equation, which requires a complex and rather lengthy test procedure.

RESULTS AND DISCUSSION

Optical evidence from nonmicrowaved and microwaved samples showed that rapid microwave heating induces stress cracking in the iron ores. Stress cracking can be readily seen in the following SEM photomicrographs. The specimen shown in figure 1*A* is a typical representation of as-received (nonmicrowaved) Michigan magnetite. The two lighter phases are iron-bearing minerals and the darkest phase is the siliceous gangue. Shown in figure 1*B* is the magnetite specimen after microwaving at 3 kW for 25 s. Cracking can be seen along the grain boundaries of the iron-bearing phases, as well as through some of the dark matrix silicates. Bond grindability tests have shown that the comminution energy was decreased. It is also expected that the fracturing along grain boundaries will result in cleaner liberation and greater surface exposure of the minerals during extractive processing. The as-received (nonmicrowaved) sample of Minnesota taconite is shown in figure 2*A*. Similar stress cracking can be seen in figure 2*B* after microwave exposure for 23 s at 3 kW. As in figure 1, the darkest phase is the siliceous gangue mineral and the lighter phases are the iron-bearing oxides.

It is recommended in the Bond procedure that the product discard size be close to the actual product size produced by conventional grinding practice, which can be as small as minus 500 mesh. However, as a matter of expediency during laboratory testing, the coarsest discard is desired because the time required for grinding and sieving is shortened considerably. Therefore, preliminary grindability tests were conducted to determine the largest product discard size that would give consistent and accurate values for the Bond work index. The Bond work indexes of as-received and microwaved iron ores for product mesh sizes of minus 48, 65, and 100 were determined. The values of the work indexes obtained for mesh sizes of minus 100 and 65 were reasonably constant for each ore tested in comparison to the values obtained with a minus 48-mesh product. This indicates that the use of the finer mesh size product would yield a more accurate and consistent value of grindability. Bond values were subsequently determined and reported using the minus 100-mesh discard product.

Figure 1

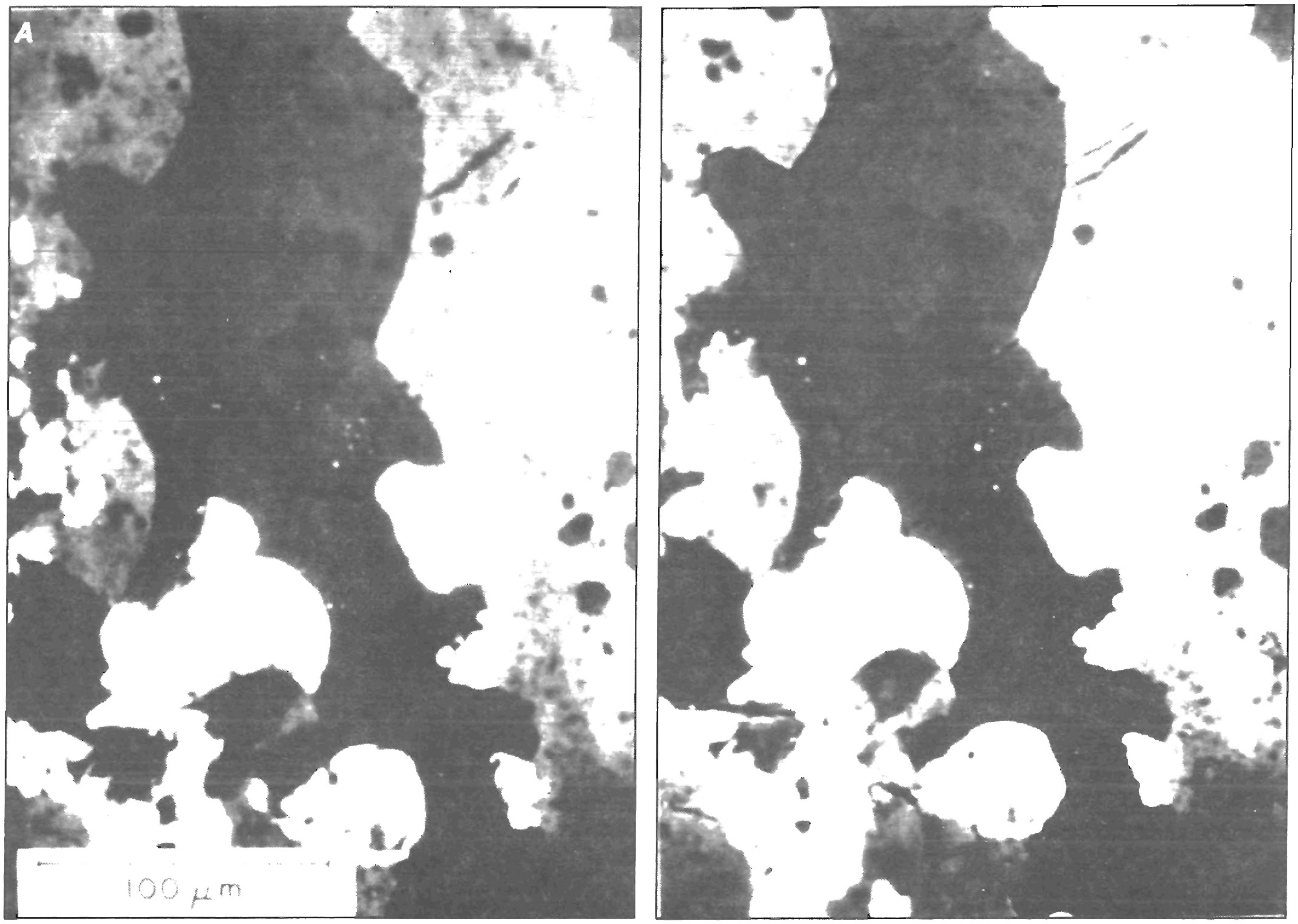


Comparison of nonmicrowaved and microwaved Michigan magnetite ore. A, Nonmicrowaved (lighter phases are iron-bearing minerals and darkest phase is siliceous gangue); B, microwaved ore showing stress cracking.

Once the preliminary experiments had established the required ground particle size of the discard product, the effect of microwave heating on the grindability and work index of the ores was determined. Results are shown in table 1. Approximately 6,000-g lots of minus 6-mesh feed were heated in batches of 350 g for 210 s at 3 kW. The temperatures shown in table 1 are the average value of the maximum temperatures observed for the individual batches. The data reveal no obvious pattern, except that martitic hematite, the most difficult ore to grind, had the smallest percentage improvement of the work index, and specular hematite, the least difficult ore to grind, had the greatest percentage improvement of the work index. The accuracy of the data can be determined by a comparison with the values reported by Cleveland-Cliffs. A range of 7.72 to 9.92 kW•h/t ore was quoted for specular hematite.[6] The USBM's value of 9.50 kW•h/t ore falls within this range. The Michigan magnetite and martitic hematite samples were not crude feed, but part of the recirculating load that is returned to the primary mill. According to the Cleveland-Cliffs spokesperson, this circulating feed is more difficult to grind, so the USBM's larger work index values are reasonable. A simple calculation shows that the amount of energy needed to raise the temperature of 1 t of ore to 800 °C exceeds the energy saved by the gain in grinding efficiency. Using the method of mixtures, the heat capacity of the iron ores was calculated to be, in kilowatt hours per metric ton of ore per degree Celsius, magnetite, 0.19; martitic hematite, 0.21; specular hematite, 0.18; and taconite, 0.17. For example, to raise the temperature of magnetite ore to 800 °C, 149.94 kW•h/t ore is required. This is obviously far more than the 3.31 kW•h/t ore that is saved by improving the grindability with microwave heating.

[6]Private communication from J. P. Hebbard, research coordinator, Cleveland-Cliffs Iron Co., Jan. 1987.

Figure 2



Comparison of nonmicrowaved and microwaved Minnesota taconite ore. A, Nonmicrowaved (lighter phases are iron-bearing minerals and darkest phase is siliceous gangue); B, microwaved ore showing stress cracking.

Table 1.—Effect of microwave heating on grindability and work index of iron ores

Iron ore	Average microwave temperature, °C	Grindability, g per mill revolution	Work index kW•h/t ore	Decrease in work index, pct
Michigan magnetite:				
As received	NAp	1.41	16.25	NAp
Microwaved	840	1.89	12.78	21.4
Martitic hematite:				
As received	NAp	1.25	17.93	NAp
Microwaved	940	1.42	16.15	9.9
Specular hematite:				
As received	NAp	2.71	9.50	NAp
Microwaved	840	3.77	7.25	23.7
Minnesota taconite:				
As received	NAp	1.62	14.50	NAp
Microwaved	880	2.07	11.86	18.2

NAp Not applicable.

Studies were conducted to increase the sample heating rate at 3 kW using the throughput applicator. The ore temperature was varied by changing the speed of the sample as it moved through the applicator. The Bond grinding results shown in table 2 are very encouraging. A substantial decrease in the work index of taconite, 13.4 pct, was obtained at a relatively low bulk temperature of 197 °C in comparison to the 880 °C for a batch-heated sample. This improvement of grindability at a lower temperature improved the cost effectiveness of microwave-assisted grinding. Increasing the bulk sample temperature to 252 °C further improved the grindability, but at a lesser rate. These data show that a significant improvement in the work index was possible by rapid heating to relatively low bulk temperatures.

Recent data reported by McGill and others (*6*) demonstrated that a greater incident power level significantly increases the heating rate of many minerals. Since the stress forces generated by heating depend on the heating rate as well as the temperature, it may not be necessary to heat an ore to a high temperature. Rapid and selective heating of ores to relatively low temperatures may result in differential stressing that is economically advantageous.

Preliminary studies were conducted to improve the technique and reduce the energy requirements for inducing stress fracturing. The tests were conducted at the USBM's, Twin Cities Research Center (TCRC) using a 6-kW, 2,450-MHz power supply in conjunction with a continuous, belt-fed applicator. A taconite ore, contained in a shallow ceramic boat, was heated as it passed through the microwave field of radiation. Immediately after treatment, an average temperature was determined by probing the sample with a thermocouple. The Reserve Mining taconite ore was heated to temperatures of 230, 540, and 610 °C by controlling the speed at which the ore traversed the microwave heating zone. Temperatures throughout the sample were considerably more uniform in comparison to the 350-g batch operations at 3 kW. The Bond grindabilities and work indexes of the samples are shown in table 3 and compared with those for taconite data from table 1. The results show that even at a low temperature of 230 °C, stress fracturing occurred, which improved grinding efficiency.

Table 2.—Effect of microwave temperature on grindability and work index of Reserve Mining taconite ore

Sample temperature, °C	Grindability, g per mill revolution	Work index, kW•h/t ore	Decrease in work index, pct	Microwave duration, s
As received	1.62	14.50	NAp	0
127	1.69	14.00	3.4	5.6
144	1.71	13.87	4.3	7.3
197	1.93	12.56	13.4	11.7
252	1.95	12.46	14.1	15.4
880[1]	2.07	11.86	18.2	210

NAp Not applicable.
[1]Sample heated in batch operation. Other samples heated in throughput applicator. All samples microwaved at 3 kW.

Table 3.—Effect of microwave temperature on grindability and work index of Minnesota taconite ore

Sample temperature, °C	Grindability, g per mill revolution	Work index, kW•h/t ore	Microwave duration, s	Microwave power, kW
Reserve Mining:				
As received	1.62	14.50	NAp	NAp
230	1.65	14.28	8	6
540	1.72	13.60	18	6
610	1.87	12.89	29	6
880	2.07	11.86	210	3
Minntac:				
As received	1.45	15.88	NAp	NAp
100	1.43	15.99	4	12
106	1.47	15.66	4	16

NAp Not applicable.

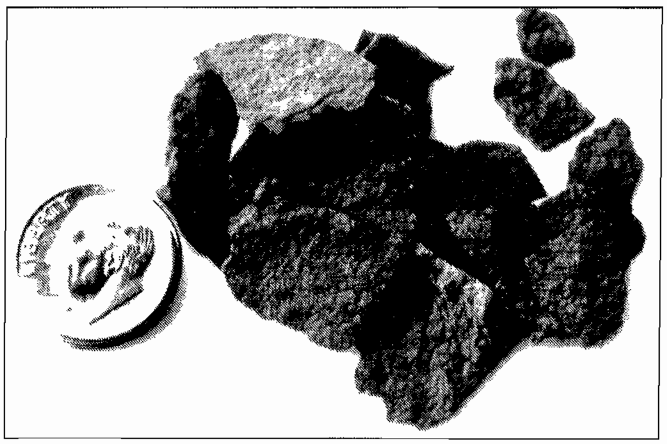
Additional studies were conducted at the TCRC facility after modifications were made to the belt-fed applicator. An external 16-kW, 2,450-MHz power source was coupled to the applicator, replacing the 6-kW supply. A minus 6-mesh Minntac taconite ore was continuously fed through the applicator and microwaved at levels of 12 and 16 kW. The Bond grindability results are shown in table 3. No improvement in the work index was obtained at either power level for the temperatures tested. Microwaving to higher temperatures may have improved the grindability, but the cost effectiveness would have decreased. Shown in table 4 are the results of studies with a Minntac minus 19-mm rod mill feed. Microwaving at 16 kW showed a strong effect of feed size on stress cracking. Grindability was improved by greater than 20 pct at an average temperature of 126 °C in comparison to the as-received taconite rod mill feed. Figure 3 shows an example of exploded taconite fragments. Approximately 95 W/cm² of microwave radiation intensity for 1.1 s produced the violent explosion with no arcing. In figure 4, a 19-mm taconite pebble is shown split in half with some arc melting present for the same intensity and time of exposure.

Table 4.—Effect of temperature and power level on grindability of Minntac taconite minus 19-mm rod mill feed microwaved for 4.8 s

Microwave power, kW	Sample temperature, °C	Grindability, g per mill revolution	Improvement of grindability, pct
NAp	[1]	4.25	NAp
12	105	4.37	2.8
	105	4.37	2.8
	105	4.34	2.1
	105	4.40	3.5
	115	4.53	6.6
	135	4.40	3.5
16	110	4.98	17.2
	125	5.00	17.6
	125	5.09	19.8
	130	5.36	26.1
	130	5.23	23.1
	130	4.87	14.6
	135	5.30	24.7

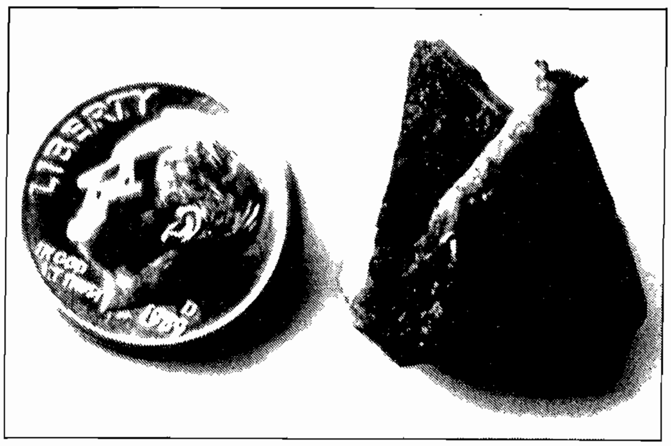
NAp Not applicable.
[1]As received.

Figure 3



Exploded taconite fragments resulting from violent explosion with no arcing (95 W/cm² for 1.1 s).

Figure 4



Split 19-mm taconite pebble with high-intensity arc melting at two points (95 W/cm² for 1.1 s).

CONCLUSIONS

Microwave energy induces thermal-stress cracking that decreases the grinding energy. However, based on energy savings alone, microwaving to improve the grindability of the iron ores was not cost effective. By improving the grindability, changes occur in the grinding circuit that may decrease comminution costs. If the ore is easier to grind there would be less wear of the mill, mill liner, and milling medium. Improved grindability would also result in an increased throughput and the amount of recycled ore would be decreased. These factors would contribute to reducing comminution costs per ton of ore. When factors in the extractive process are considered, the use of microwave energy may become even more attractive. For example, thermal expansion of the selectively heated minerals and no expansion of the adjacent gangue matrix also offers the potential to more cleanly liberate ore minerals from the gangue at larger ground particle sizes. Cleaner liberation of the ore mineral at larger particle size would reduce the grinding energy requirements as well as improve the concentrate grade and metal recovery after beneficiation. More selective leaching, more efficient flotation, or better magnetic separation could also be accomplished on the microwaved ores. It is this combination of improved grindability and cleaner liberation of minerals that may make the use of microwave treatment economically viable in mineral extraction processes.

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